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(54) Method and apparatus for performing optical time domain reflectometry.

(57) In a method and a corresponding apparatus for performing optical time domain reflectometry predetermined time sequences of light signals (A′, B′) are injected into an optical fiber and the signals backscattered from the fiber are correlated with the injected sequences. The injected time sequences are selected according to a specific code such that after each element in the code represented by "1" or "-1" a predetermined number of elements represented by "0" is provided. Depending on the number of inserted "0"s after each "1" or "-1" sidelobes in the correlation product appear at certain predictable positions. By choosing the numbers of inserted "0"s differently for different injections, the resulting sidelobes appear at different positions in the corresponding correlation products. From the correlation products of such different injections, a composite fiber response can be derived wherein sidelobes are substantially eliminated. The codes used can be derived, for example, from Golay complementary codes.

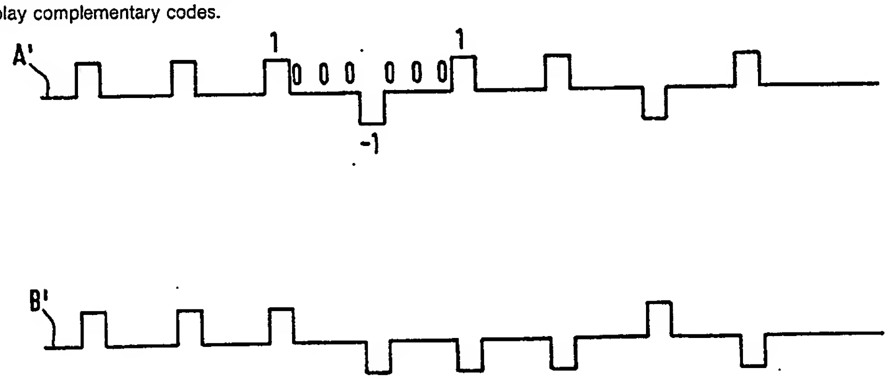

Fig. 4

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EP 0 379 609 A1

METHOD AND APPARATUS FOR PERFORMING OPTICAL TIME DOMAIN REFLECTOMETRY

The invention relates to a method and a corresponding apparatus for performing optical time domain reflectometry according to the preamble of claim 1 . Such a method can be used in optical fiber testing to determine faults and losses in a fiber under test.

A method and a corresponding apparatus as in the preamble of claim 1 are known from EP-A-0 269 448 . According to the known optical time domain reflectometer (OTDR), sequences of light pulses are injected into an optical fiber and the backscattered light pulses are correlated with the injected sequences of light pulses to generate a representation of the amplitude of the backscattered signal as a function of the time elapsed since the injection of the sequence or as a function of the distance from the input end of the fiber. The pulse sequences injected into the fiber are, for example, complementary pseudorandom sequences such as sequences in accordance with Golay codes. A pair of complementary sequences A and B has the property that the autocorrelation product of A has sidelobes which are complementary to the sidelobes of the autocorrelation product of B, i.e., sidelobes which are located at the same point in the time spectrum and which have amplitudes of equal magnitudes, respectively, but of opposite sign. Consequently, if the correlation products corresponding to the complementary sequences are superposed, the sidelobes cancel, and there remains only a signal originating from actual reflections in the fiber. Ideally, the superposed correlation products of the injected complementary pulse sequences with the signals reflected from a distinct reflection location in the fiber such as a fracture, is a single sharp peak, a so-called delta function. The use of complementary pulse sequences provides a better signal-to-noise ratio than conventional reflectometry wherein only a single pulse is injected into the fiber and the reflection of this particular pulse is detected.

In practice, the sidelobe cancellation is not perfect because of the non-ideal characteristics of the signal processing circuitry. For example, saturation of electronic components such as receiver or analog-to-digital converter due to strong power levels of the reflected signal can lead to non-linearities which destroy the complementary nature of the correlation products. As a consequence thereof, correlation sidelobes may appear on the measured backscattering curve that are large enough to distort or even mask a large reflection peak.

Relative to the prior art, the invention according to claim 1 or 8 solves the problem to provide a method and a corresponding apparatus for performing optical time domain reflectometry on a light transmitting medium according to the preamble of claim 1 or 8 which avoids the disadvantages caused by the mentioned non-linearities.

According to an underlying principle of the invention, at least two different time sequences of light signals are injected into the light transmitting medium and afterwards correlated with the corresponding reflected signals from the medium, respectively. The different injected time sequences can be described as being derived from a common basic sequence by insertion of a predetermined number of light signals of zero power level after each light signal of the basic sequence. Stated in other words, if the basic sequence is represented by a sequence of "+1" and "-1" the injected time sequences can be described as being derived from the basic sequence by insertion of a predetermined number of "0"s after each "+1" or "-1 ". The different injected time sequences differ from each other by the number of light signals inserted after

inserted after each light signal of the conventional sequence. For obtaining a fiber response curve which permits to determine faults and losses, the backscattered sequences of light signals are correlated with the injected sequences.

According to an embodiment of the invention, the overlapping of sidelobes for different injections is avoided by proper selection of the number of inserted "0"s. The number of inserted "0"s increased by one, subsequently called the "extension factor", for a first injection and the extension factor for a second injection are chosen to be prime relative to each other, i.e., non-divisible by each other. By this selection of

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sequently, an embodiment of the invention is explained in detail with reference to the drawings:

gure 1 is a block diagram of an apparatus for performing optical time domain reflectometry according to an embodiment of the invention.

Figure 2 shows two complementary Golay code sequences A and B as they are used in the prior art.

Figure 3 illustrates the incomplete cancellation of sidelobes due to non-linear behaviour in the prior art.

Figure 4 shows modified complementary Golay code sequences A' and B' according to an embodiment of the invention.

Figure 5a shows the fiber response curve for injection of a single pulse.

Figure 5b shows the fiber response curve for injection of modified sequences according to the invention.

Figure 6 shows an example of a fiber response curve with peaks corresponding to strong reflections and associated sidelobes.

Figures 7a and 7b illustrate the substitution of data values at sidelobe positions if no peaks corresponding to a reflection are adjacent.

Figures 8a and 8b illustrate the substitution of data values at side lobe positions if a peak corresponding to a reflection is adjacent.

Figure 9 shows the fiber response curve after substitution of data values at sidelobe positions.

Figure 1 schematically depicts an OTDR according to the invention and an optical fiber 10 under test coupled to the OTDR by an optical coupler 9. The OTDR comprises a timing control circuit 1 which provides timing signals to a word generator 2, to an A/D converter 3 , to an averaging circuit 4, to a signal

= 2 L•δ(n) (1)

otes correlation of two sequences , δ is the delta function, i.e. a sharp peak. The signal m a fiber in response to an injected signal is a convolution between the injected signal and response h(n) which can also be denoted as single pulse return function.

mplementary sequences A(n) and B(n) are injected into a fiber, the backscattered signals n) which are detected are a convolution (denoted by the symbol *) of the fiber impulse d the injected sequences, respectively, i.e., the following equations apply:

n) (2a)

n) (2b)

Correlation of equation (2a) with A(n) and of equation (2b) with B(n) and addition of the two intermediate results yields:

$y(n) = S_A(n) \odot A(n) + S_B(n) \odot B(n) = (h(n) * A(n)) \odot A(n) + (h(n) * B(n)) \odot B(n)$ (3)

Due to the distributive and associative properties of convolution and correlation the parentheses can be regrouped so that equation (3) can be rewritten as

$y(n) = (A(n) \odot A(n)) * h(n) + (B(n) \odot B(n)) * h(n) = (A(n) \odot A(n) + B(n) \odot B(n)) * h(n)$ (4)

Using the autocorrelation property according to equation (1), the final result is then

$y(n) = h(n) * 2L\delta(n) = 2L \bullet h(n)$ (5)

As can be seen from equation (5) the reconstructed response is 2L times larger than the response to a digital impulse. From this it becomes clear that reflectometry using sequences of injected light signals with subsequent correlation of the backscattered signals leads to an improvement of the signal-to-noise ratio as compared with single pulse reflectometry without impairing the resolution.

The foregoing considerations regarding the sequences A(n) and B(n) use an abbreviated notation for these sequences. In practice, since there are no negative light power levels, i.e., a "-1" cannot be realized by light signals, the sequences are split up in two subsequences, respectively. The two subsequences for the A sequence are designated as A^+ and A^- whereby A^+ is obtained from A by replacing all the "-1"s in A by "0 "s and leaving all "1 "s unchanged. The subsequence A^- is the logical complement of the subsequence A^+ i.e., a "1" in the sequence A^+ corresponds to a "0" in the subsequence A^- and vice versa. Thus, the equation applies: $A = A^+ - A^-$ The sequence B is correspondingly split up into two subsequences B^+ and B^- such that B^- is the logical complement of B^+ and the equation applies: $B = B^+ - B^-$

In a practical measurement situation, the sequences A^+ and A^- are successively injected into the fiber under test and the measured backscatter signals are $h(n) * A^+(n)$ and $h(n) * A^-(n)$ respectively. These two expressions are then subtracted from each other to yield the backscatter signal $S_A(n)$ (see the above equation (2a)) for the whole sequence A(n) :

$S_A(n) = h(n) * A(n) = A^+(n) * h(n) - A^-(n) * h(n)$.

Similarly, the sequences B^+ and B^- are successively injected into the fiber and for the backscatter signal $S_B(n)$ (see the above equation (2b)), the following applies:

0, 1, 1, 1, 0, 1

e 3 illustrates the incomplete cancellation of sidelobes because of non-linearities. It can be seen beak at position 0 is surrounded by sidelobes at positions up to L- 1 points apart to the left and to . As a consequence thereof, a measured signal will be distorted in the neighbourhood of strong s. These distortions are substantially eliminated by the present invention.

basic step to overcome the sidelobe problems is now explained with reference to Figure 4. The a according to the invention is to modify the conventional code sequences such as the sequences in Figure 2 by inserting a predetermined number of zero bits between each pair of bits in the es A and B. In the example shown in Figure 4, three additional bits are inserted such that the code sequences A' and B' have the following form:

Sequence A': 1,0,0,0,1,0,0,0,1,0,0,0, -1,0,0,0,1,0,0,0,1,0,0,0, -1,0,0,0,1,0,0,0

Sequence B': 1,0,0,0,1,0,0,0,1,0,0,0, -1,0,0,0, -1,0,0,0, -1,0,0,0,1,0,0,0, -1,0,0,0

In Figure 4, some of the elements("1" ,"-1" , "0") of the injected sequence A' are indicated. It can also be seen from Figure 4 which depicts the time sequence of injected signals, that the duration of an inserted "0" signal corresponds to the duration of the "1" or "-1" signals. Since three "0" signals are inserted in the example shown, the time interval during which "0" signal is applied is three times as long as the time interval during which a single "1" or "-1" signal is applied.

In practice, the modified sequences are also split up in two subsequences, respectively, which are successively injected into the fiber under test as described above. The subsequences are formed from the modified sequences A' and B' according to the above construction principle (replacing "-1" by "0" to obtain A^+ , and forming the complement of A^+ to obtain A^-) with the understanding that the inserted "0's" remain unaffected by these two transformations. In other words, the subsequences for the modified sequences A' and B' are obtained by inserting the predetermined number of zero bits between each two bits of the subsequences A^+ , A^- , B+ , B^- of the unmodified sequences A and 13. To give a practical example, the subsequences for the modified sequences A' and B' in the above example are as follows:

A'^+ : 1,0,0,0,1,0,0,0,1,0,0,0,0,0,0,0,1,0,0,0,1,0,0,0,0,0,0,0,1,0,0,0

A'^- : 0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0

B'^+ : 1,0,0,0,1,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0

B'^- : 0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,0,0,0,0,1,0,0,0

Generally, the number of zero bits inserted between each pair of bits in a conventional sequence is X- 1

only be unequal to zero for $k = \pm i \bullet X$, $i = 0, 1, \ldots, L-1$. In order to reduce computation time calculate only the terms of the autocorrelation z_k which are not zero. Consequently, the ion (9) could be incremented in steps of X.

the invention, modified code sequences are injected into an optical fiber, the return signal the sum of the individual autocorrelations is computed according to equations (3) - (5). veral post-processing procedures are employed to get a final result without disturbance es due to inherent non-linearities in analog circuitry nor by sidelobes due to saturation of Three post-processing procedures are described in the following.

Procedure I

According to this procedure, the fiber is successively probed with modified code sequences A_i' and B_i' with different extension factors X_i i.e. the number of zero bits inserted is different for different injections. The individual correlated results are then summed up to generate a final result y_F. The final result y_F can be written as :

$$y_F = \sum_i y_i$$

whereby, using equation (4), the following relationship applies:

$y_i = (A_i'(n) \odot A_i'(n)) * h(n) + (B_i'(n) \odot B_i'(n)) * h(n)$.

As explained above, the expressions A_i' and B_i' are abbreviated notations. It applies:

$A_i' = A_i'^{+}(n) - A_i'^{-}(n)$ and $B_i' = B_i'^{+}(n) - B_i'^{-}(n)$.

In this final result, the magnitudes of the sidelobes are reduced relative to magnitudes of the peaks caused by reflections in the fiber as compared to the invidual correlated results since the peak positions remain the same for different injections whereas the sidelobe positions vary from injection to injection in accordance with the varying extension factors. In that way, the peak-to-sidelobe ration is virtually increased. It might happen that the sidelobe positions of successive measurements overlap, i.e. that a sidelobe of a measurement with a first extension factor occurs at the same location as another sidelobe of a measurement with a second extension factor. Such overlap of sidelobes can be avoided by proper selection of the extension factors X_i ; a convenient way, for example, is to select the extension factors prime to each other , i.e. such that the numbers X_i cannot be divided by each other. In that way excellent results can be achieved as demonstrated in Figures 5a and 5b.

Figure 5a shows the fiber response to a single injected pulse , and Figure 5b shows the response to a modified 64 bit sequence processed according to the just described procedure. The curves shown in Figures 5a and 5b were measured in equivalent measurement times. The quality improvement achieved by the invention can clearly be seen.

The procedure No.I is preferably used as a first processing step at the beginning of each new measurement for rapidly decreasing the noise imposed on the fiber response h(n) and for roughly determining the positions of reflections. Particularly when using very short pulse widths which, in the prior art would cause a noisy backscattering impulse response, procedure No. I provides the advantage that a representation of the fiber response can be obtained quickly that allows to perceive some rough fiber

positions can be calculated according to equation (6). Then, according to an essential step of the ...re, the sample values at the sidelobe positions are replaced by the mean value of the two adjacent ...values. If, however, at least one of the two adjacent data points represents a sidelobe or even a ...n, this point cannot be used for computation of the substitution value. Then, two cases have to be ...shed:

...) If two or more sidelobes are arranged adjacent to each other and no reflection borders on this ... sidelobes, each substitution value is calculated as lying on a straight line that connects the two ...n-distorted samples of the fiber response. Figure 7a shows a detail of the fiber response curve of ... and with sidelobes indicated by the sample values or data points 71, 72, and 73. Figure 7b shows ...lting curve after performing the procedure just described. The sample values 71, 72, and 73 have ...placed by sample values indicated by "s such that a straight line connecting the two outer non-distorted sample values 70 and 74 is formed.

2.) If a reflection is located adjacent to a sidelobe, then the sample value at the sidelobe position is calculated by a straight line approximation as illustrated in Figure 8. In Figure 8a, the sidelobe position is at 81 and the peak position is at 82. The approximation is performed such that a straight line is extended from the left across the undisturbed sample point 80 as indicated by the dotted line in Figure 8a. The sample value on the other side of the reflection peak cannot be used since in most cases a reflection is followed by a splice or other discontinuity. The result of the approximation is shown in Figure 8b. Generally, a dense concentration of sidelobes can be avoided by choosing an extension factor X which is great enough. Figure 9 shows the result after application of the procedure II to the data in Figure 6.

Procedure III

After application of the procedures I and/or II procedure III serves for further sidelobe cancellation. The key step of this procedure is to substitute all disturbed sample values at sidelobe positions by "correct" values from earlier measurement results. For that purpose, the fiber is successively probed, as in procedure I, with modified code sequences with different extension factors.

In order to obtain a good noise reduction for all samples during the whole measurement process, multiple overlap of sidelobe positions in successive measurements has to be avoided. The only parameter that affects the sidelobe positions is the extension factor X .All chosen extension factors should be prime relative to each other, i.e., the extension factors should not be divisible by each other.

Each of the three described procedures or a combination of these procedures offers the possibility to improve the sidelobe to peak ratio or even to eliminate sidelobes that may appear in nonlinear systems.

According to an embodiment of the invention, a corresponding apparatus for performing optical time domain reflectometry comprises a memory of 4 k words allowing 2000 data points for representing the fiber impulse curve, and a code length of the modified Golay codes A' or B' of up to 1000 bits, respectively. Therefore, during each measurement the following condition has to be fulfilled:

$$L' = X \bullet L < 1000 \qquad (11)$$

whereby L' is the number of bits of the modified sequence and L is the number of bits of the unmodified sequence. The extension factor varies in the range from three to ten times the number R of strong reflections in the fiber. Consequently, the maximum usable code length L is given by the relationship:

$$\frac{1000}{10 \cdot R} < L < \frac{1000}{3 \cdot R} \qquad (12)$$

For example, if 9 strong reflections have been detected in a measurement i.e., if R = 9 then X will be

reduced or avoided. If, for example, a data value obtained during a first injection is obscured by a sidelobe, the true sample value which is unaffected by sidelobes can be obtained by injecting at least one other sequence with a different extension factor such that the sidelobe for this injection is at a different position.

Claims

1. A method of performing optical time domain reflectometry on a light transmitting medium, for example an optical fiber, the method comprising the following steps:

a) injecting time sequences of light signals into the medium, the sequences comprising light signals of two different power levels,

b) detecting the light signals reflected from the light transmitting medium ,

c) correlating the detected signals from the light transmitting medium with the injected signals ,

characterized in that

d) at least two different time sequences of light signals are injected into the light transmitting medium (10) and correlated with the detected signals, respectively, with the different sequences (A_1',B_1' ; A_2',B_2') being derived from a common basic sequence (A,B) by insertion of a predetermined number of light signals of the same power level after each light signal of the basic sequence, and with the different time sequences differing from each other by the number (X- 1) of the inserted light signals.

2. A method according to claim 1, **characterized** in that the common basic sequence is a set of complementary sequences (A,B), for example a set of two Golay complementary sequences (A,B) such that the at least two different time sequences injected into the light transmitting medium are modified complementary sequences with the modification relative to the basic complementary sequences consisting in that a predetermined number of light signals are inserted after each light signal of the conventional complementary sequence.

3. A method according to any of the claims 2,

characterized by the following steps :

- successively injecting a plurality of modified complementary sequences into the fiber (10) with the number (X- 1) of inserted light signals of the modified sequences being different from each other for different injections,
- superposing the correlation results of the individual injections for generating a composite measurement result, thus leading to a reduction of the magnitudes of sidelobes relative to the magnitudes of peaks originating from reflections in the fiber.

4. A method according to claim 2 or 3,

characterized by the following additional steps:

- determining the positions of peaks originating from reflections in the fiber (10),
- calculating all possible sidelobe positions according to the equation

$SP = PP +/- i X$;

whereby SP denotes the sidelobe positions, PP denotes the peak positions, and i may be any integer from 1 to L- 1 , L being the code length of the basic sequence and - replacing the measured data values at sidelobe positions by calculated data values such that the calculated data values aproximate adjacent sample values.

5. A method according to claim 2 or 3,

- detection means (12,13) for de
tecting the light signals reflected from the light transmitting medium (11),
- signal processing means (4,5)
for correlating the detected signals from the light transmitting medium with
the injected signals,
- display means (6) for displayir
g the correlated results,
characterized in that
a word generator (2) connected
to the light injection means (7,8,9) is provided for generating sequences of

(10), the sequence comprising light signals of two different power levels ,
- detection means (12,13) for detecting the light signals reflected from the light transmitting medium (11),
- signal processing means (4,5) for correlating the detected signals from the light transmitting medium with the injected signals,
- display means (6) for displaying the correlated results,
characterized in that
a word generator (2) connected to the light injection means (7,8,9) is provided for generating sequences of electrical pulses for activating the light injection means such that at least two different time sequences of light signals are injected into the light transmitting medium (10), with the different sequences (A_1',B_1' ; A_2',B_2') being derived from a common basic sequence (A,B) by insertion of a predetermined number of light signals of the same power level after each light signal of the basic sequence, and with the different time sequences differing from each other by the number (X- 1) of the inserted light signals.

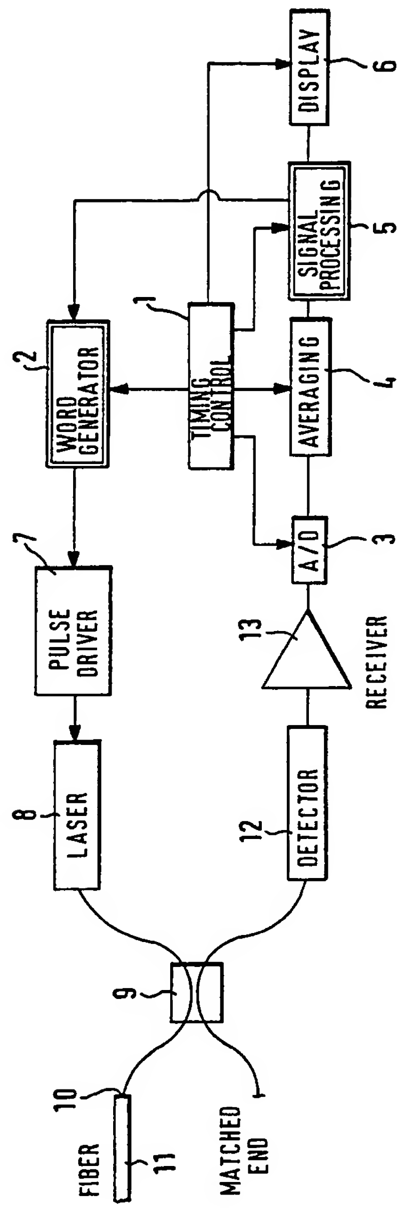
DISPLAY
6
SIGNAL PROCESSING
5
1
TIMING CONTROL
2
WORD GENERATOR
AVERAGING
4
A/D
3
7
PULSE DRIVER
13
RECEIVER
8
LASER
12
DETECTOR
9
10
FIBER
11
MATCHED END

Fig.1

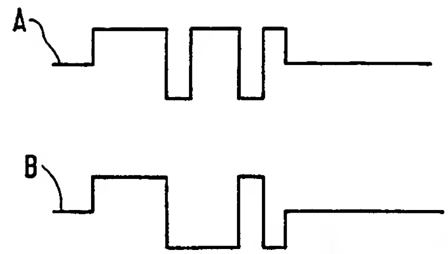

Fig. 2 (PRIOR ART)

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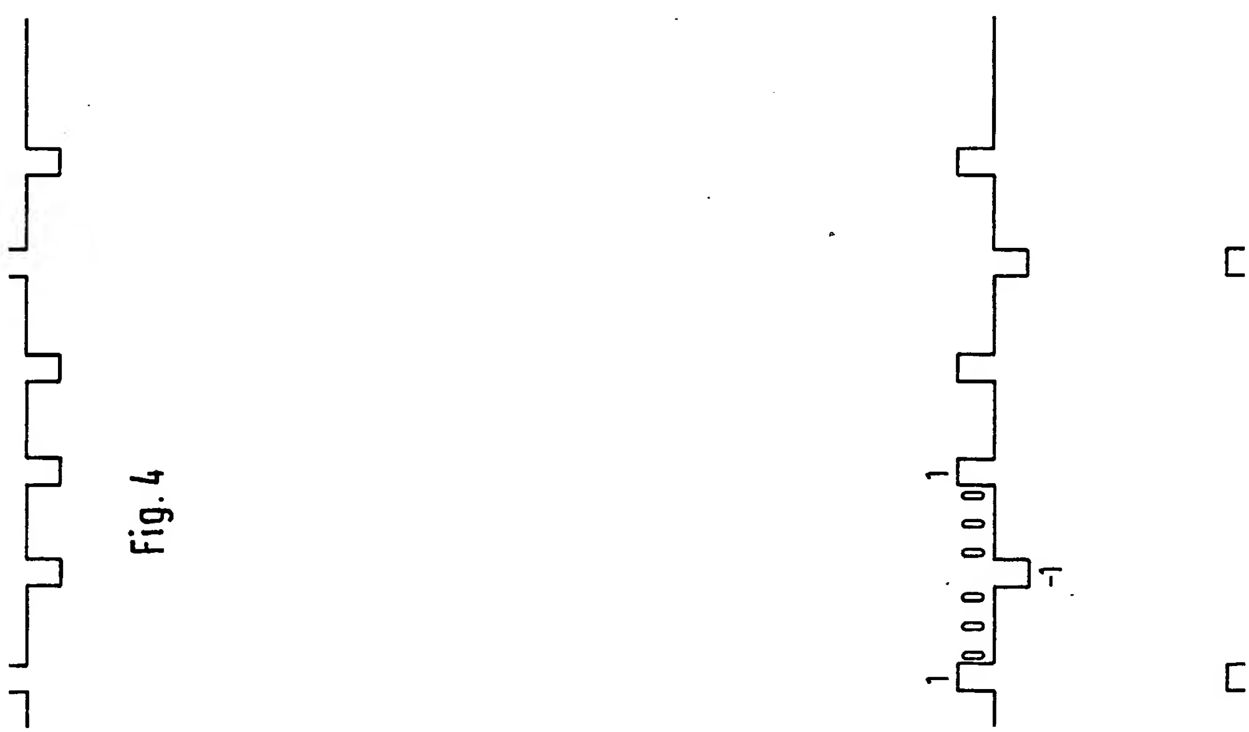


Fig. 4

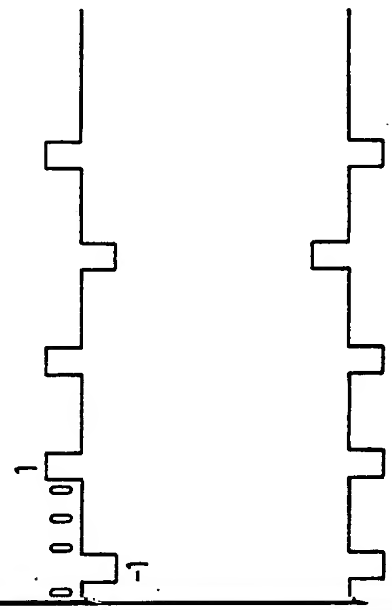


Fig. 4

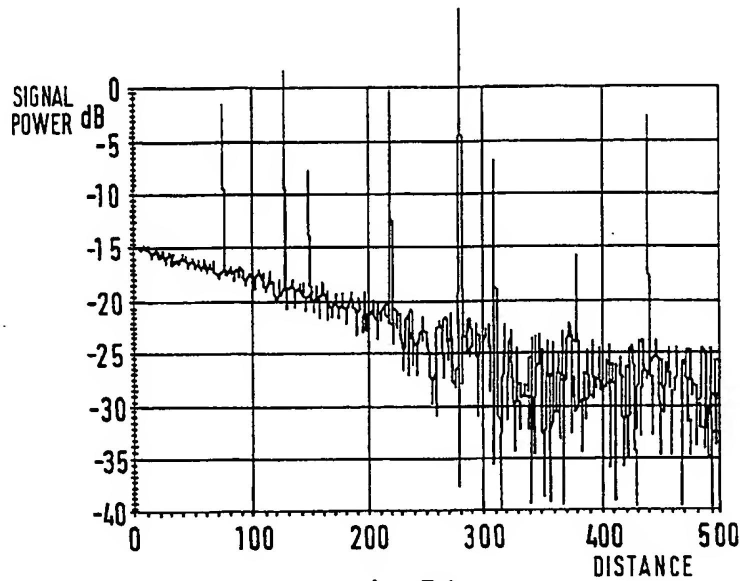
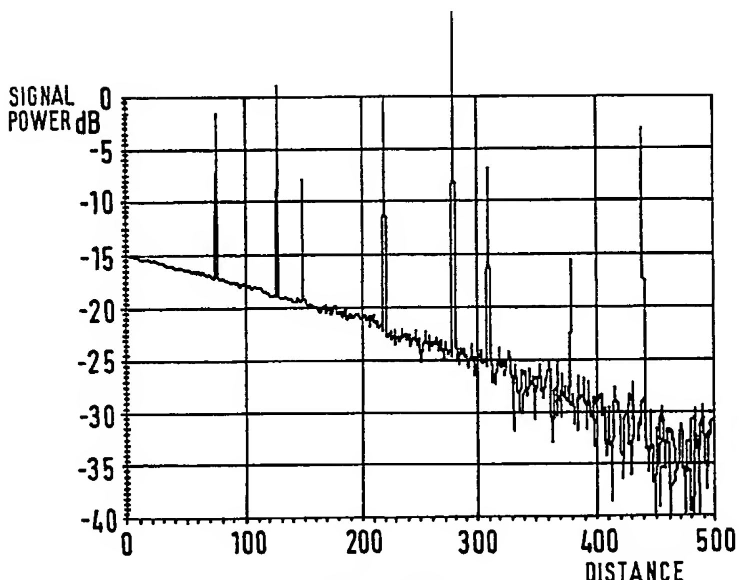

SIGNAL POWER dB
0
-5
-10
-15
-20
-25
-30
-35
-40
0
100
200
300
400
500
DISTANCE

Fig.5A


SIGNAL POWER dB
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-5
-10
-15
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-25
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-35
-40
0
100
200
300
400
500
DISTANCE

Fig.5B

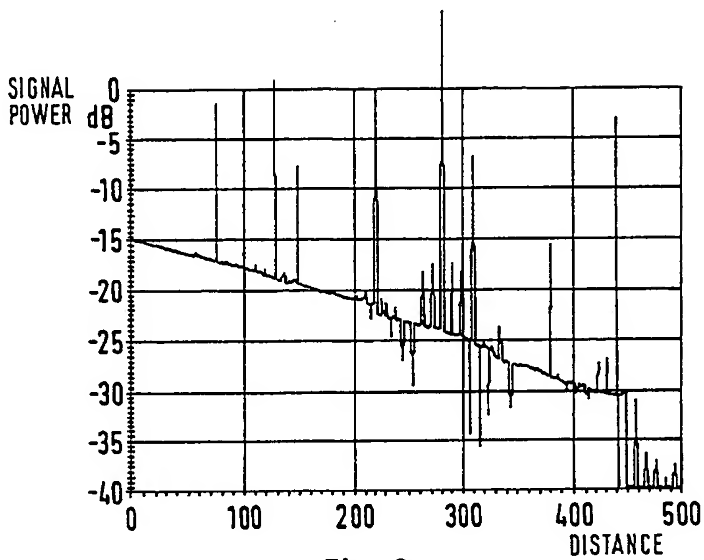

Fig. 6

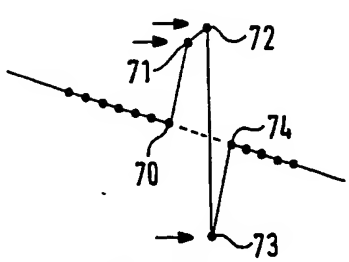

Fig. 7A

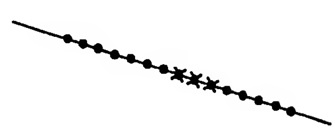

Fig. 7B

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ment dépos

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EUROPEAN SEARCH REPORT

Application Number

EP 89 10 1168

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
D,A	EP-A-0 269 448 (HEWLETT PACKARD CO.) * The whole document * ---	1,8	G 01 M 11/00
A	EP-A-0 258 843 (TEKTRONIX INC.) * The whole document * ---	1,8	
A	WO-A-8 707 014 (J.K.A. EVERARD) * The whole document * -----	1,8	
			TECHNICAL FIELDS SEARCHED (Int. Cl.5)
			G 01 M 11

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	21-09-1989	VAN ASSCHE P.O.

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